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RESEARCH MEMORANDUM

PRELIMINARY ANALYSIS OF A NUCLEAR-POWERED
SUPERSONIC AIRPLANE USING RAMJET ENGINES

By Richard J. Weber and Donald J. Connolley

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RESEARCH MEMORANDUM **CLASSIFICATION CHANGED**

PRELIMINARY ANALYSIS OF A NUCLEAR-POWERED SUPERSONIC AIRPLANE

To UNCLASSIFIED

USING RAMJET ENGINES

By Richard J. Weber and Donald J. Connolley

By authority of *OSCAR*

Ne-2 Date *6-30-71*
Blm 9-16-71

SUMMARY

Performance estimates are made for a family of airplanes designed to cruise at a Mach number of 4.25 using proposed General Electric AC-210 ramjet engines. The airplanes carry a payload of 10,000 pounds and a crew of one. For a two-engined configuration the biological shield weight is calculated to be between 60,000 and 100,000 pounds, depending on the degree of refinement in design, the size of the crew compartment, and the relative position of the pilot and the engines. With a 100,000-pound shield, the maximum cruise altitude is estimated to be 71,500 feet at an airplane gross weight of 215,000 pounds. For a 60,000-pound shield, the ceiling is 80,600 feet at an airplane gross weight of 170,000 pounds. Installing more engines raises the airplane ceiling but at the expense of greater weight. Airplane gross weight is fairly sensitive to changes in shield weight and engine weight; maximum altitude is affected to a lesser extent. Variations in engine thrust have a large effect on altitude.

INTRODUCTION

At the request of the Air Force, a brief design-point study was carried out at the NACA Lewis laboratory of the feasibility of a manned nuclear-powered supersonic airplane using ramjet engines. The airplane was designed to cruise at a Mach number of 4.25 with a payload of 10,000 pounds and a crew of one. The weight and the thrust of the engines were based on the estimates of reference 1.

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The study was carried out in three phases:

- (1) Calculation of the required shield weight as a function of the position of the pilot relative to the engines
- (2) Estimation of the gross weight and the cruise drag of a family of airplanes designed for various conditions
- (3) Combination of the first two phases with engine thrust estimates to find the maximum design flight altitude and the corresponding airplane gross weight.

The majority of the airplane calculations were based on what is felt to be a rather conservative shield design. The object was to determine if reasonable airplane performance could be obtained without demanding a very highly refined shield configuration of minimum weight. In addition, however, the effect on the airplane of modifying the shield to obtain lighter weight was considered.

One of the major problems associated with the use of this airplane, as with any ramjet vehicle, is that of attaining the high speeds requisite for satisfactory engine operation. Even with the use of variable-geometry components, the engines could probably not accelerate the airplane from Mach numbers lower than about 2.5 to 3.0; some auxiliary boosting device is therefore necessary. The present analysis is restricted to a design-point study, and no consideration was given to the problems of take-off, acceleration, and climb to the design cruise condition.

ANALYSIS

This section outlines the major assumptions made with respect to the ramjet engines, the radiation shield, and the airframe.

Engines

The calculated performance of several nuclear-powered ramjet engines is presented in reference 1. The configurations differed from each other only in detail and closely resembled conventional ramjet engines with the addition of a reactor core placed in the combustion chamber. An isentropic external-compression diffuser was used in conjunction with a completely expanding convergent-divergent nozzle. The reactor core was made of parallel uranium-impregnated ceramic tubes. The engine airstream was heated to about 2840° F as it flowed through and around the hollow centers of the ceramic tubes.

4475 The engine designated by reference 1 as AC-210-1 was arbitrarily selected for use in the present study. The reported variation of net thrust with altitude is shown in figure 1 for the design flight Mach number of 4.25. Also shown is the estimated propulsive thrust after accounting for nacelle drag. The total length of the engine (tip of spike to nozzle exit) is 57.5 feet, and the maximum diameter is 8.4 feet. The weight of the reactor core and control is given as 26,015 pounds. In the present analysis the engines are assumed to be contained within the fuselage, with an installed weight per engine of 27,500 pounds. This value is somewhat lower than the corresponding estimate of reference 1, which includes the nacelle weight of an isolated engine; the difference is considered to be included in the fuselage weight.

No effort was made in the present study to optimize the engine size or the design of the inlet diffuser and exhaust nozzle.

Radiation Shield

A unit-type radiation shield was assumed to enclose the crew compartment. A divided shield or a unit shield around the engines was not considered because of the large inlet and exit ducts required to pass the engine airflow. The airplane structure is thus not protected from any possible deleterious effects of radiation, but no study was made of this problem. The instruments and payload are at least partially protected because the shield is between them and the engines.

Dosage rate. - The range of the manned nuclear airplane cannot be considered as unlimited; the pilot's endurance is restricted by the total amount of radiation he is permitted to receive. For a flight of the order of 6000-nautical-mile radius at a Mach number of 4.25, the flight time is about 5 hours. Assuming a dose of 20 rems per mission leads to the selection of a design dose rate of 4 rems per hour in the present study.

Basic shield configuration. - The shield was assumed to enclose a crew compartment 6 feet in length and 3 feet in diameter. The shield consists of an inner layer of lead and an outer layer of water. The layers are in the form of hollow elliptical right cylinders with flat ends (see fig. 2). The lead acts to attenuate the gamma rays. The water attenuates the neutrons and also aids in attenuating the gamma rays.

Source of radiation. - The radiation was assumed to consist of neutrons and gamma rays emitted from General Electric AC-210-1 engines. For the shield calculations, the engines were assumed to be operating at full power at an altitude of 70,000 feet. This corresponds to a power level of approximately 360 megawatts per engine.

Detailed calculations were carried out to determine the shield thickness necessary for shielding against radiation from two engines. These calculations were then modified for shielding against radiation from one and four engines.

Shield-weight calculations. - The shield-weight calculations were carried out in two parts. The first was to determine the shield thickness necessary to shield against the direct radiation. The second was to modify this shield thickness to account for the additional dose due to air-scattered radiation.

For the direct-dose calculation, the source of neutron and gamma-ray radiation was divided into two parts, one corresponding to the radiation from the front of the reactor, and the other corresponding to radiation from one-half of the cylindrical side surface of the reactor. The value of one-half was chosen because to an observer in the crew compartment only one-half of the side surface of the reactor is visible. Core relaxation lengths for both neutron and gamma rays were evaluated for use in these direct-dose calculations. By using these core relaxation lengths and the dimensions of the reactor, equivalent disk sources of radiation were evaluated for both the front and the side of the reactor. The angle between the normal to the equivalent side disk and a line drawn to the crew compartment is very large in all the aircraft configurations considered in these calculations. Therefore, the source of radiation from this disk was modified by a cosine distribution. The angle between the front disk and the crew compartment was small in most of the cases considered; so the correction was not made in these cases.

The shield thickness for the direct radiation on the sides of the crew compartment was calculated only at the position 90° from the top. This is the position on the sides of the crew compartment which receives the maximum direct dose. The thicknesses at the top and the bottom of the crew compartment were determined, as described later in this section, by air-scattering considerations. It was assumed that an ellipse drawn through these thicknesses, top and sides, would adequately describe the variation in the shield thickness at all points on the periphery of the shield. A few calculations were carried out to substantiate this assumption.

By assuming the sources mentioned previously, the direct-dose calculation for the neutron radiation was performed at each point of interest. A thickness of water was assumed and, with the aid of Bulk Shield Reactor data (ref. 2), the dose rate on the inside of the crew compartment was evaluated. Since the angle of incidence of this radiation was not zero, this dose rate was modified by a slant-penetration factor and a factor which accounts for the fact that the crew compartment acts like a directional detector rather than an isotropic detector. The slant-penetration factor was obtained by fitting an approximate equation to curves by

Chapman (ref. 3). This equation was then used to extend Chapman's curves to the ramjet dimensions.

The gamma-ray shield thicknesses were determined by using Bulk Shield Reactor data (ref. 2) for the attenuation in the water and by assuming exponential attenuation with a buildup factor in the lead. No acceptable slant-penetration data were available for the gamma rays; so this correction was not made. Therefore, the actual lead thickness necessary for gamma-ray shielding is probably somewhat smaller than that calculated.

For the scattered-radiation shield thickness, the reactor was assumed to be a point source of 3 Mev gamma rays and 3 Mev neutrons. Since the relaxation lengths in air, at the altitude considered, are very long, only a single scattering phenomenon was considered. This calculation established the shield thickness for the front of the crew compartment; and, since the angle of incidence of the direct radiation at the top and the bottom of the crew compartment is very nearly 90° , only a small fraction of the incident direct radiation would penetrate the shield at these points. Therefore, the shield thickness at these points was determined by the scattered radiation.

Airplane

On the basis of preliminary calculations, a reference airplane was designed that was expected to yield good performance at a Mach number of 4.25 and an altitude of 70,000 feet (see table I and fig. 3). The effect of redesigning the airplane was then investigated as each of the following parameters was varied: wing loading, weight, number and location of engines, shield weight, design altitude, and airplane configuration.

The major assumptions made for the reference airplane are as follows.

Configuration. - A canard configuration is used, with no horizontal tail. The center of pressure of the canard surface is 20 feet from the fuselage nose. The canard-surface area and the vertical-tail area are each equal to 15 percent of the wing area. For stable flight, the canard surface must be at a higher angle of attack than the wing is; the ratio of angles of attack is set at 1.5 during cruising.

A delta plan form is employed for both the wing and the canard surface, with a biconvex airfoil section. The aspect ratio is 2.5 and the thickness ratio, 3.5 percent.

Fuselage. - The fuselage consists of two parabolic half-bodies of revolution joined at their maximum diameters. The pilot's compartment is located at this point. With a nominal maximum shield diameter of 9 feet, the maximum fuselage diameter is chosen as 10 feet. A length of 60 feet

for the forward parabolic section of the fuselage was found to represent a good compromise between weight and drag. Two engines are assumed to be installed in the fuselage, 60 feet aft of the pilot's compartment, with scoop inlets. The total length of the fuselage is 130 feet. The locations and the weights of the components contained within the fuselage are given in the following table (where the shield weight is based on results of the previously described shield calculations):

| Component | Distance from nose, ft | Weight, lb |
|---------------------|------------------------------|---------------|
| Payload | 45 | 10,000 |
| Instruments | 50 | 3,000 |
| Shield, pilot, etc. | 60 | 100,000 |
| Engines (two) | 120 | 55,000 |

An additional weight equal to 8 percent of the total airplane gross weight is included to account for landing gear and miscellaneous equipment.

Structure. - The weights of the fuselage and the wing were calculated with semiempirical equations that were found in previous studies to yield realistic results. The structural material is stainless steel. Its strength was varied with the average equilibrium skin temperature that is experienced at different flight altitudes after allowing for thermal radiation. The wing was designed for a normal load factor of 2.5. Other stressed components of the airplane were designed for a safety factor of 1.5.

Drag. - It is assumed that the final design is refined to avoid unfavorable aerodynamic interference effects. The total drag of the configuration is approximated by summing the drags of the wing, the fuselage, and the engines, each considered as isolated components. Laminar boundary layers and favorable pressure-field interactions are not considered.

RESULTS

Based on the nominal assumptions described in the ANALYSIS section, the gross weight and the cruise drag of a number of airplanes designed for various cruise altitudes were calculated. The altitude at which the drag is equal to the available engine thrust defines the cruise altitude and the corresponding gross weight of the reference airplane. Other series of airplanes were then analyzed in the same manner to determine the resulting cruise altitude and the gross weight when arbitrary changes were made in the major components, such as shield weight, and so forth.

The calculated gross weight and the drag of the airplanes are given in appendix A. In this section these data are combined with the engine

thrust schedule of figure 1. The resulting data show the altitude capability and the gross weight of the nuclear ramjet airplane and indicate the sensitivity of these characteristics to changes in the major design variables. Except when otherwise specified, two engines are used. All performance is for design-point airplanes at a Mach number of 4.25.

Shield weight. - The results of the preliminary shield-weight calculations are presented in figure 4. All combinations of separation distance and separation angle of interest in the present study are found to require shield weights of 90,000 to 100,000 pounds. This led to the selection of a nominal crew-compartment weight of 100,000 pounds (including the weight of the pilot and associated equipment). Several methods of reducing this weight are conceivable. For example, it is estimated that a more refined design (with rounded corners, a hydrocarbon substituted for the water, and the crew compartment shortened by 1 ft) would weigh about 60,000 pounds. Further, if only one engine were used, the shield weight could be lowered to about 45,000 pounds. Alternatively, the refined technique might be used to reduce the radiation dosage to the pilot without changing the shield weight.

The effect that the shield-weight variations would have on the altitude capability and gross weight of the airplane is shown in figure 5. Reducing the shield weight from 100,000 to 60,000 pounds would improve the ceiling from 71,500 to 80,600 feet. At the same time, the gross weight is reduced from 215,000 to 170,000 pounds. This effect is large since the shield represents approximately 50 percent of the total airplane weight.

Engine weight. - Figure 6 illustrates the effect of changes in the engine weight. The airplane ceiling is comparatively insensitive to this parameter. A 50-percent increase in engine weight from the assumed value of 27,500 pounds would lower the maximum altitude by only 5000 feet. However, the gross weight would rise from 215,000 to 250,000 pounds.

Number of engines. - Figure 7 illustrates the effect of varying the number of installed engines. The solid line indicates use of the conservative shield-weight calculations, and the dashed line represents the lighter, more refined shield design. In both cases the shield weight is varied with the number of engines because of the changed amount of radiation emitted. The shield weights used are given in the following table:

| Number of engines | Shield weight, lb | |
|-------------------|-------------------|---------|
| | Conservative | Refined |
| 1 | 85,000 | 45,000 |
| 2 | 100,000 | 60,000 |
| 4 | 110,000 | 70,000 |

Changing the number of engines, and hence the thrust, by a factor of two would change the cruise altitude by about 15,000 feet if all other factors remained constant. However, of course, the total installed engine weight and also the shield weight change. In addition, redesigning the airplane for the new altitude affects the lift-drag ratio and the structural weight.

An airplane weighing only 106,000 pounds is seen possible by using one engine with a refined shield, but the airplane ceiling is then only 65,000 feet. Higher altitudes are obtained by installing more engines, but at the cost of a substantially heavier airplane.

Nozzle velocity coefficient. - In the other sections of this report, the exhaust-nozzle velocity coefficient has been taken as 0.975. In the final airplane design, the effective velocity coefficient might well be less than 0.975 as a result of (1) internal nozzle losses, (2) divergence losses due to nonaxial discharge, and (3) thrust losses due to incomplete expansion in order to limit engine weight and external drag.

Because of the comparatively low nozzle-entrance temperature, the jet velocity of the nuclear ramjet is not much greater than the flight velocity. The engine thrust is therefore quite sensitive to variations in the jet velocity. Figure 8 illustrates how the thrust is affected by changes in the nozzle velocity coefficient.

The effect of velocity coefficient on airplane performance is shown in figure 9. Reducing the velocity coefficient from 0.975 to 0.950 has little effect on gross weight but lowers the altitude by 8000 feet.

CONCLUDING REMARKS

The estimated performance of supersonic-airplane designs using nuclear-powered ramjet engines is presented. The airplanes considered in this analysis are suitable for bombing or reconnaissance missions; they have no maneuvering capability because of thrust and structural limitations.

A representative airplane design using two engines and a comparatively heavy shield is calculated to weight 215,000 pounds and to have a maximum altitude of 71,500 feet at the design Mach number of 4.25. Still higher altitudes are possible by using more engines, although the gross weight is substantially greater. Moderate changes in engine weight have a minor effect on cruise altitude, while variations in engine thrust have a large effect on altitude.

Very substantial improvements in airplane performance may be realized by reducing the shield weight. Preliminary conservative shield calculations yielded weights in the order of 100,000 pounds (for two engines).

It is estimated that refined designs (with rounded corners, shortened crew compartment, and hydrocarbon neutron attenuation) may reduce the shield weight to about 60,000 pounds. This lighter shield results in an airplane weighing 170,000 pounds with a ceiling of 80,600 feet.

Use of only one engine permits a still lighter shield because of the reduced amount of radiation. A refined shield for this case is estimated to weigh about 45,000 pounds, resulting in an airplane gross weight of 106,000 pounds but with a ceiling of only 65,000 feet.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 19, 1957

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APPENDIX - AIRFRAME WEIGHT AND DRAG

This section presents the comparative performance of airplanes in which one or more related design parameters are varied. Unless otherwise stated, the flight altitude is 70,000 feet and all other design parameters are fixed at the values specified for the reference airplane. The comparisons are made solely on the basis of airplane total drag and gross weight, neglecting for the moment the question of whether sufficient engine thrust is available to overcome the drag. The RESULTS section considers the integrated performance of the airframe-engine combination.

Wing Loading

The effect on weight and drag of varying the design wing loading is indicated in figure 10. At the given altitude of 70,000 feet, the optimum wing loading is about 80 to 100 pounds per square foot. Lower wing loadings require larger wings and increase the gross weight, resulting in an increase in total airplane drag. On the other hand, higher wing loadings also increase the total drag because of the larger induced drag, despite the lower gross weight. Marked on the figure are the required angles of attack of the wing for the different wing loadings. The angle of attack α is related to both the wing loading and the altitude according to the following equation:

$$\alpha = \frac{W_g/S}{q dC_L/d\alpha}$$

where W_g is the gross weight, S is the wing area, q is the dynamic pressure at the given flight speed and altitude, and $dC_L/d\alpha$ is the lift-curve slope (C_L is lift coefficient), which is independent of the altitude. From figure 10 and similar curves for other altitudes, it was found that minimum drag is obtained at a wing loading corresponding approximately to a value of α of 0.08 radian (4.6°). The resulting schedule of wing loading with design flight altitude is shown in figure 11.

Shield Weight and Separation Distance

The shield surrounding the pilot's compartment is the heaviest component of the airplane and hence has a strong influence on the resulting airplane performance. Figure 4 shows the total crew-compartment shield weight as a function of reactor - crew-compartment separation distance and angular position for a dose rate of 4 rems per hour. The following table gives the thickness of lead and water for various points on the shield for a representative separation distance of 70 feet and an angular position of 6° .

| Position | Side | | Top and bottom | | Rear | | Front | |
|---------------|-------|------|----------------|------|-------|------|-------|------|
| Material | Water | Lead | Water | Lead | Water | Lead | Water | Lead |
| Thickness, ft | 2.5 | 0.8 | 2.3 | 0.5 | 4.4 | 0.83 | 2.3 | 0.5 |

The separation distance has a direct effect on airplane performance because of the resulting changes in fuselage length. Gross weight and drag as functions of shield weight and separation distance are shown in figure 12. For separation distances less than 50 feet, the fuselage was extended past the engines sufficiently so that the fuselage fineness ratio was kept equal to 12. Otherwise, it was found that the fuselage boattail drag becomes excessive. For separation distances greater than 50 feet, the aft extension was fixed at 10 feet.

Figure 12 shows that the drag and the weight are insensitive to sizable changes in separation distance. However, variations in shield weight are seen to be quite important. Superimposed on the figure is the calculated variation in required shield weight with separation distance according to figure 4. Separation distance is seen to have a nearly negligible effect in the range shown because the comparatively small changes in shield weight are offset by variations in fuselage weight.

Flight Altitude

The effect of design flight altitude on lift-drag ratio, gross weight, and drag is shown in figure 13. Higher altitudes require a larger wing to support the airplane and therefore the gross weight increases. However, the greater wing area improves the lift-drag ratio sufficiently that the total drag decreases at higher design altitudes. Lift-drag ratios range from about 5 at 60,000 feet to 6 at 90,000 feet. (These values do not include engine nacelle drag, which has been deducted from the engine thrust.)

For steady level flight the engine thrust is equal to the airplane drag. Hence, figure 13 may be interpreted as illustrating the effect on maximum cruise altitude of variations in engine thrust. It is seen that a small change in thrust produces a substantial change in the maximum design cruise altitude.

Engine Weight

The installed weight of each engine is nominally taken as 27,500 pounds in this report. The effect of variations in weight was calculated in order to determine the sensitivity of the results to changes in this assumed value. Figure 14 shows the airplane drag and gross weight as a function of engine weight for design altitudes of 70,000 and 90,000 feet.

Airplane Configuration

The reference airplane had a canard surface with engines contained in the fuselage. This was compared with a conventional wing and tail configuration. The tailed configuration was calculated to have slightly lower lift-drag ratio, to be somewhat heavier, and hence to have higher drag.

Calculations were also made for a canard configuration with the engines carried on the wing tips. For the same engine and shield weights and with no engine nacelle drag, the total airplane drag was essentially the same as that for the reference airplane. However, it is expected that an external engine mounting would increase the installation weight and involve some additional drag. Also, the external mounting was found to require greater shield weight because of a reduced axial separation between the pilot and the engines and because of a greater angle ϕ (fig. 4).

As a result of these considerations, no further work was done with either the tailed configuration or with wing-mounted engines.

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1. Corbin, A., Feathers, L. A., and Szekely, T.: Nuclear Ram Jet Power Plant - Technical Design - AC 210. Rep. XDC 56-5-81, Aircraft Nuclear Prop. Dept., Atomic Products Div., General Electric Corp., Apr. 30, 1956.
2. Blizard, E. P.: Introduction to Shield Design, II. CF-51-10-70, Oak Ridge Nat. Lab., 1952.
3. Chapman, G. T.: Slant Penetrations of Neutrons Through Water. Aircraft Nuclear Propulsion Quarterly Progress Report for Period Ending June 10, 1954. Oak Ridge Nat. Lab., July 29, 1954, pp. 117-118.

TABLE I. - WEIGHT AND DIMENSIONS OF
REFERENCE AIRPLANE

| | |
|------------------------------------|---------------|
| Weight distribution: | |
| Canard surface, lb | 1,400 |
| Wing, lb | 13,350 |
| Fuselage, lb | 14,700 |
| Fixed load, lb | 113,000 |
| Landing gear and miscellaneous, lb | 17,360 |
| Engines (two), lb | <u>55,000</u> |
| Total weight, lb | 214,810 |
| Dimensions: | |
| Canard-surface area, sq ft | 287 |
| Wing area, sq ft | 1,915 |
| Vertical tail area, sq ft | 287 |
| Wing span, ft | 69 |
| Fuselage length, ft | 130 |
| Fuselage diameter, ft | 10 |

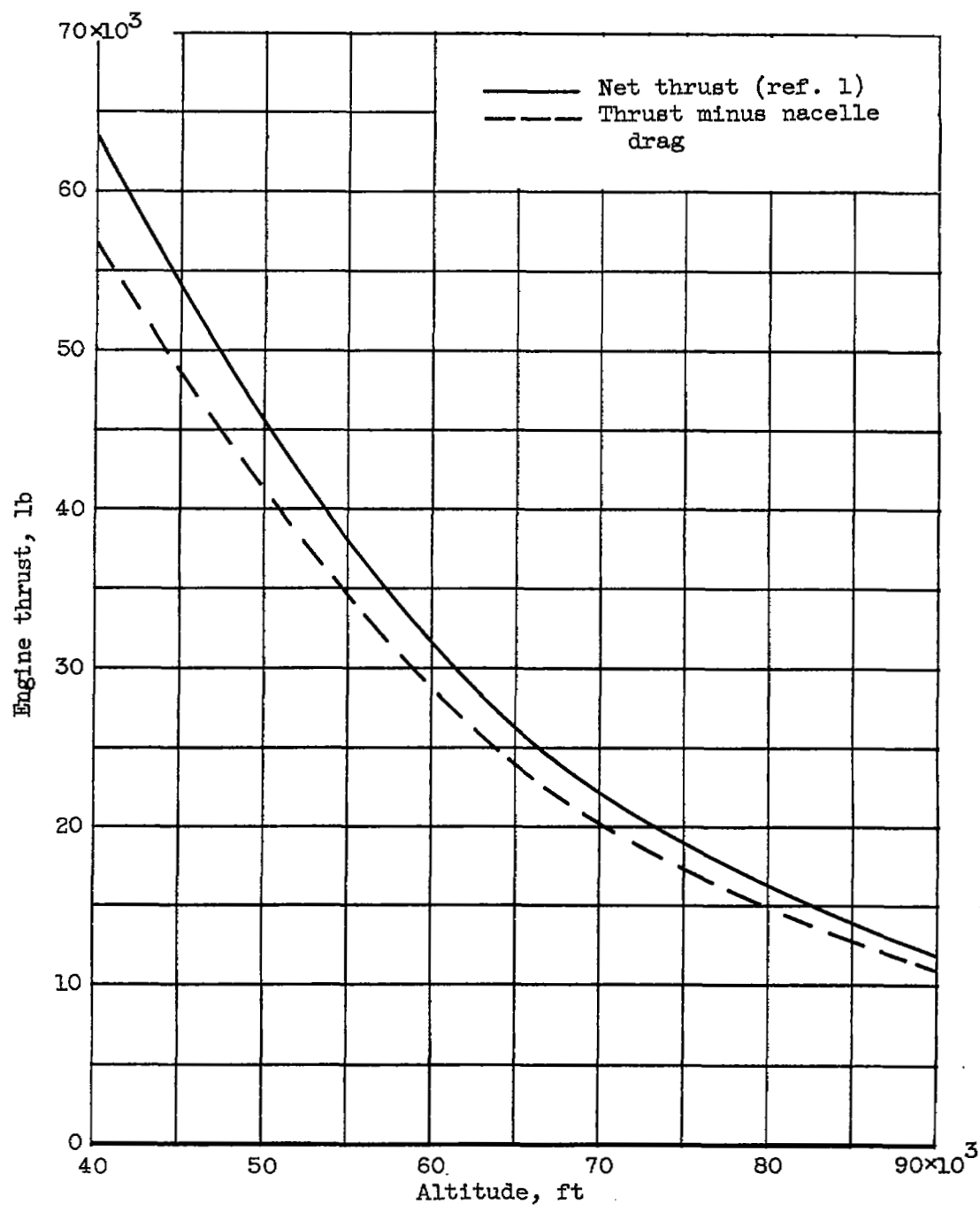


Figure 1. - Effect of altitude on thrust of General Electric AC-210-1 ramjet engine (ref. 1). Flight Mach number, 4.25.

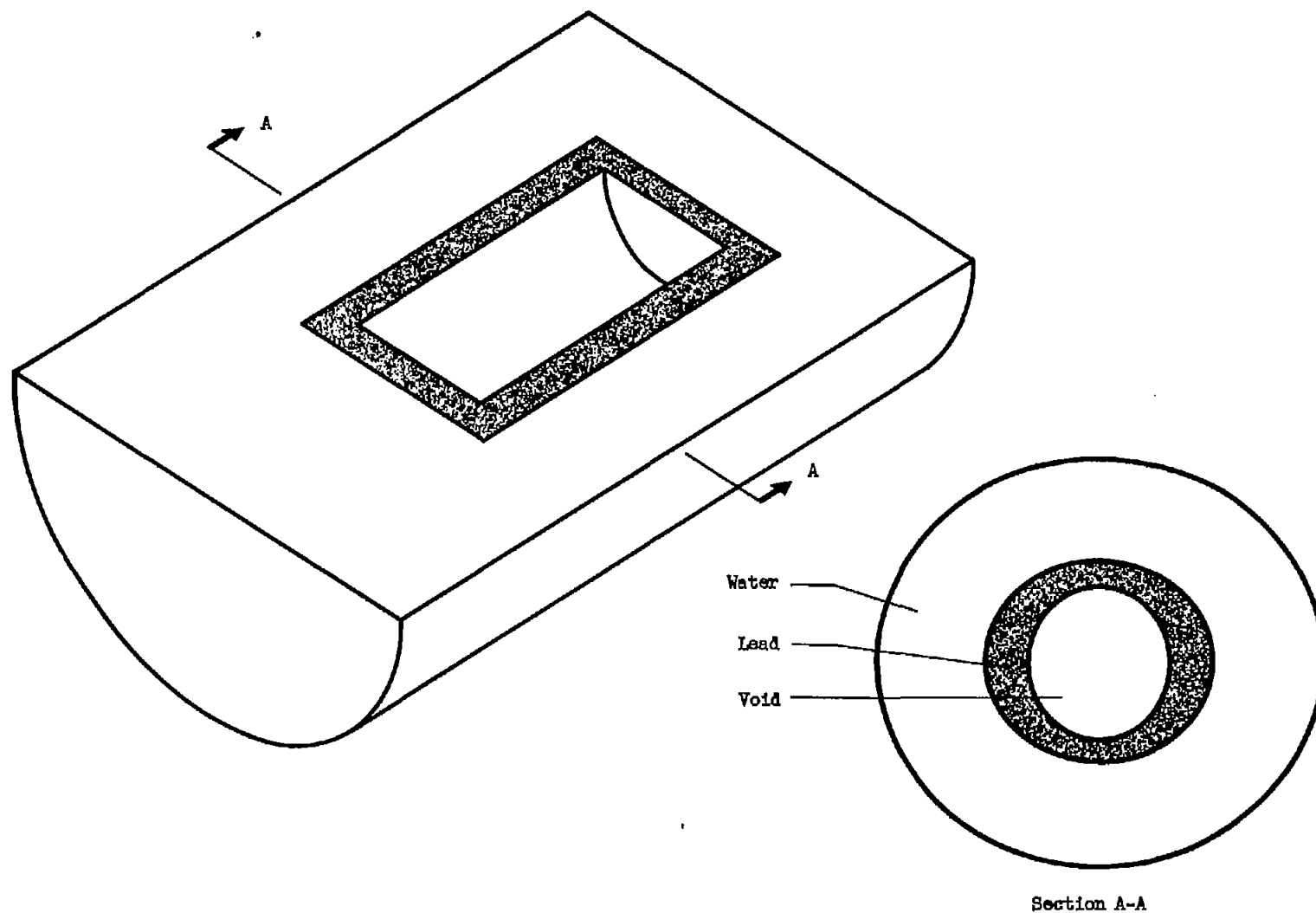


Figure 2. - Basic crew compartment and shield configuration.

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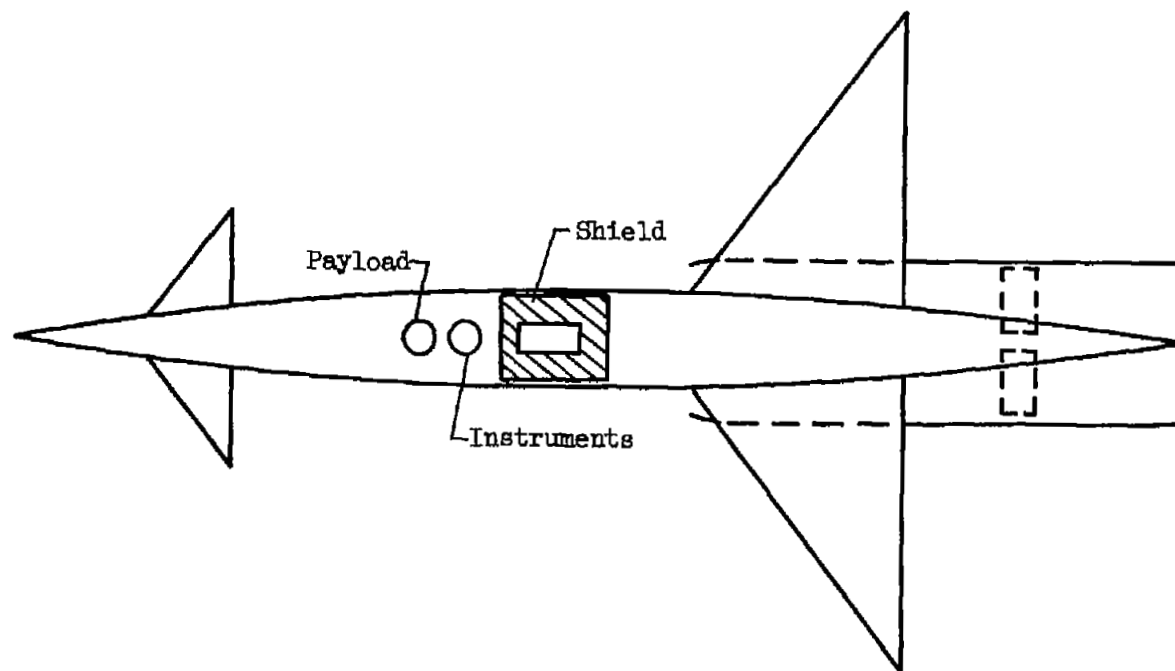


Figure 3. - Schematic diagram of reference airplane.

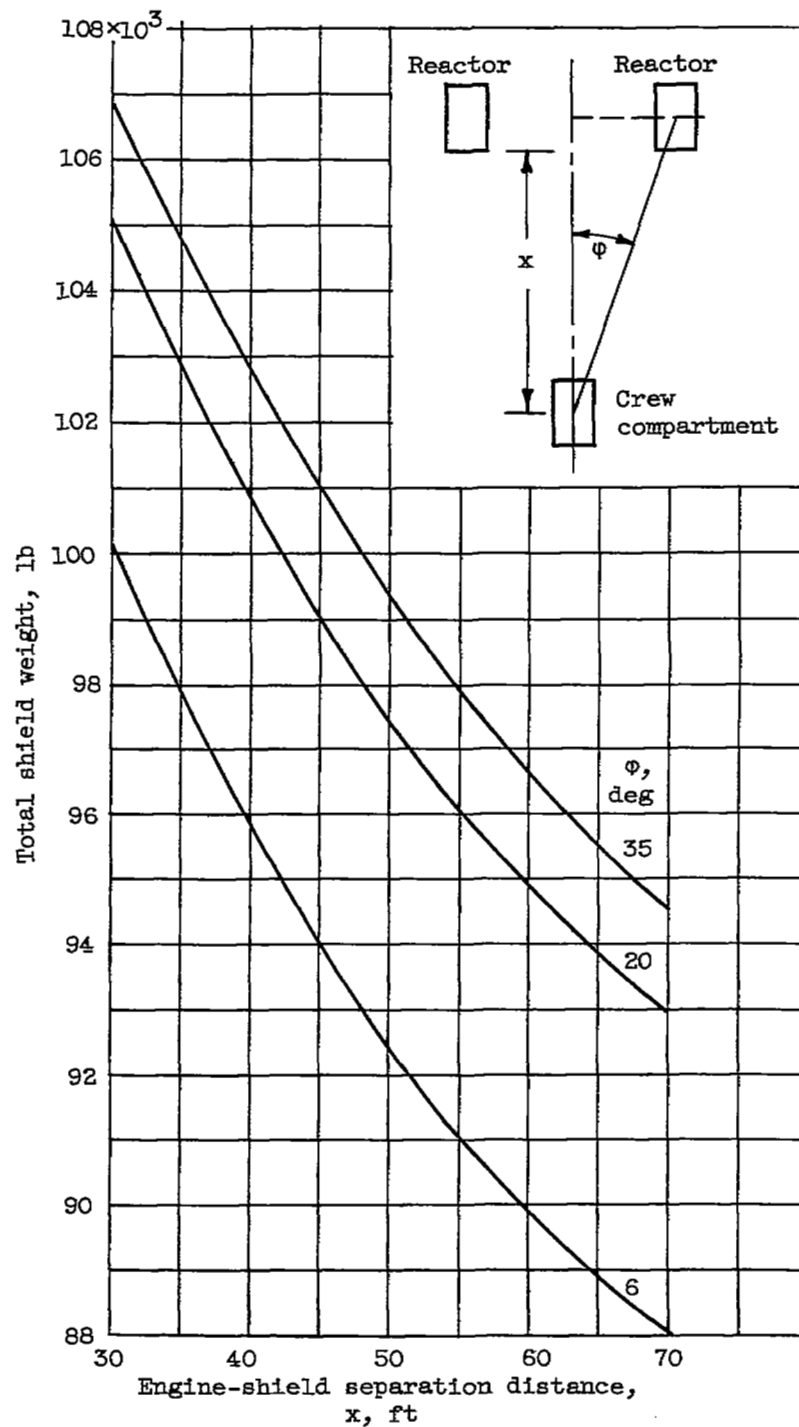


Figure 4. - Effect of axial separation distance and angle on shield weight.

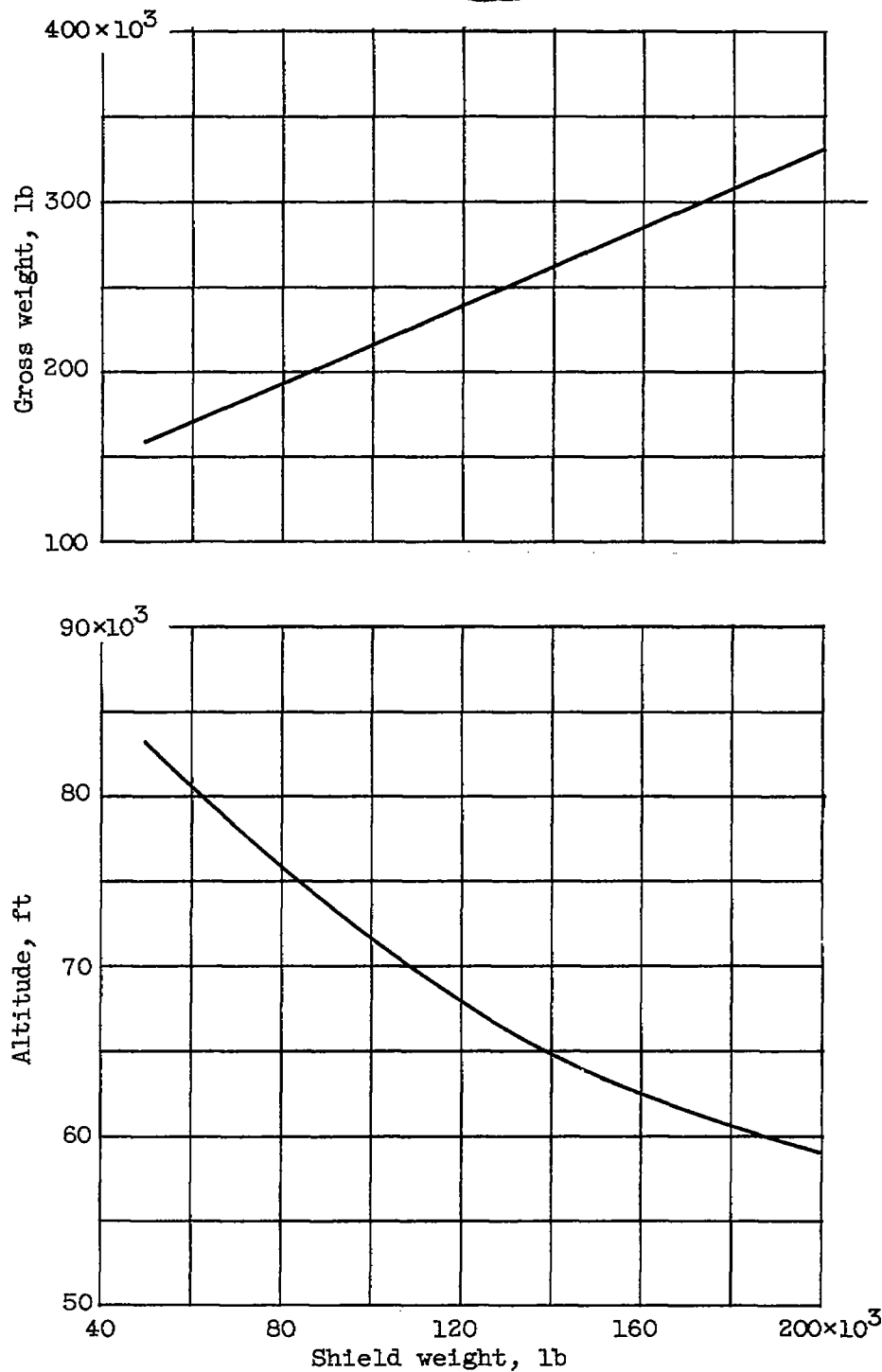


Figure 5. - Effect of variation in shield weight on maximum cruise altitude. Two engines.

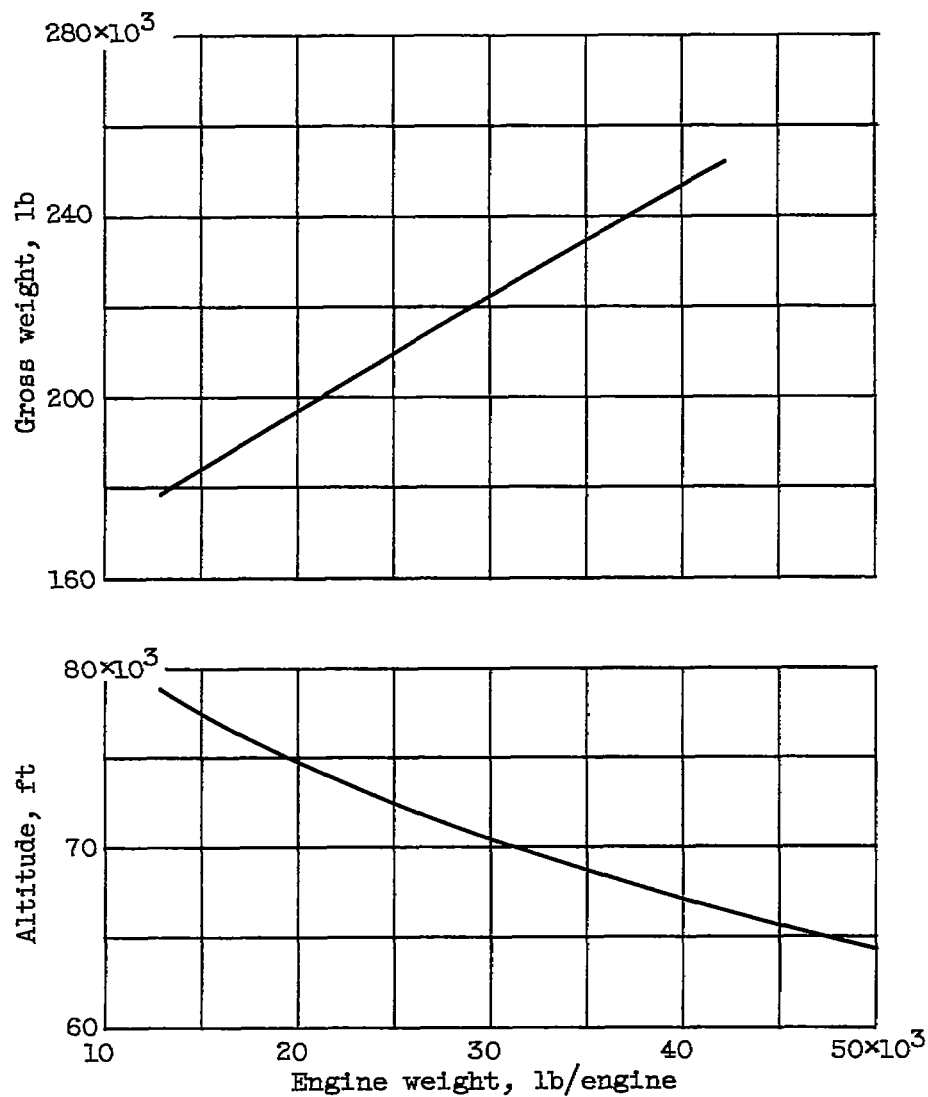


Figure 6. - Effect of variation in engine weight on maximum cruise altitude. Two engines; shield weight, 100,000 pounds.

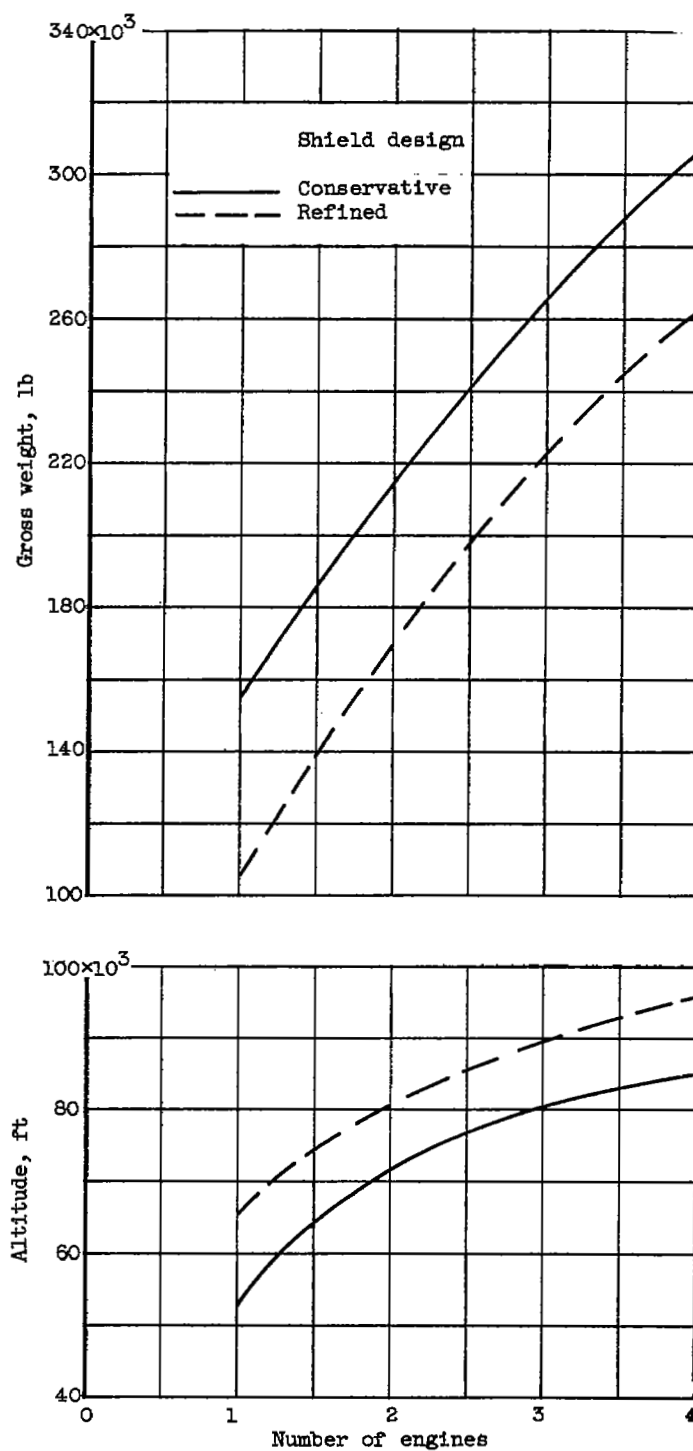


Figure 7. - Effect of variation in number of engines on maximum cruise altitude.

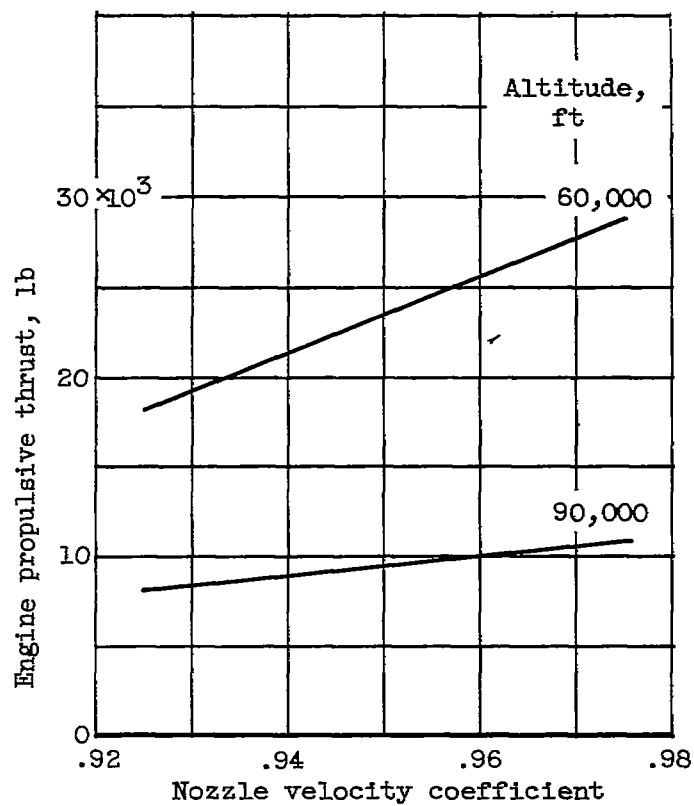


Figure 8. - Effect of nozzle velocity coefficient on engine thrust minus nacelle drag.

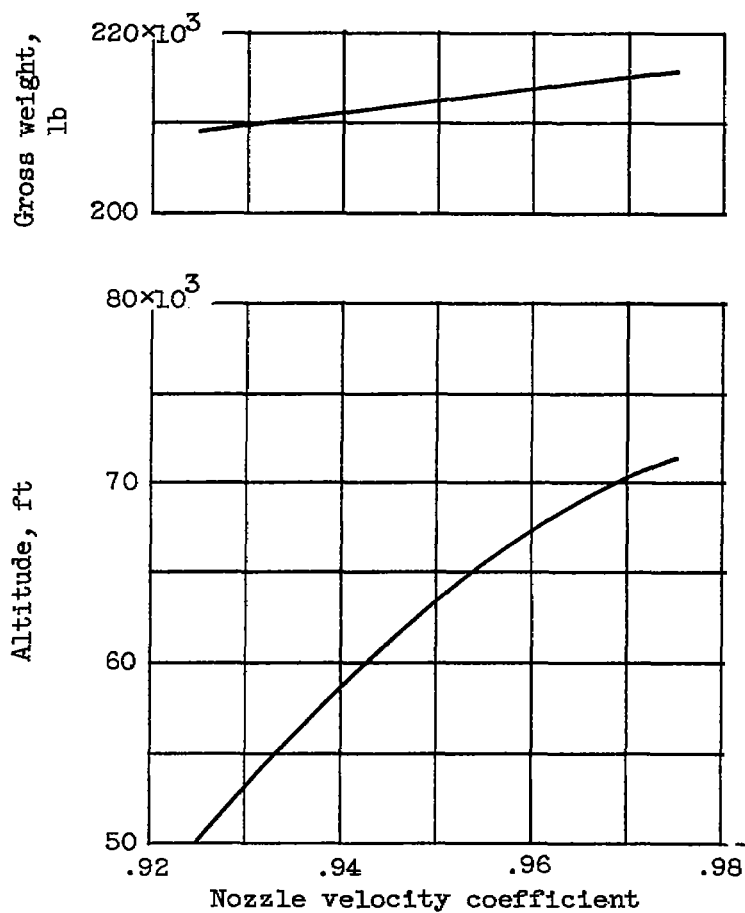


Figure 9. - Effect of variation in nozzle velocity coefficient on maximum cruise altitude. Two engines; shield weight, 100,000 pounds.

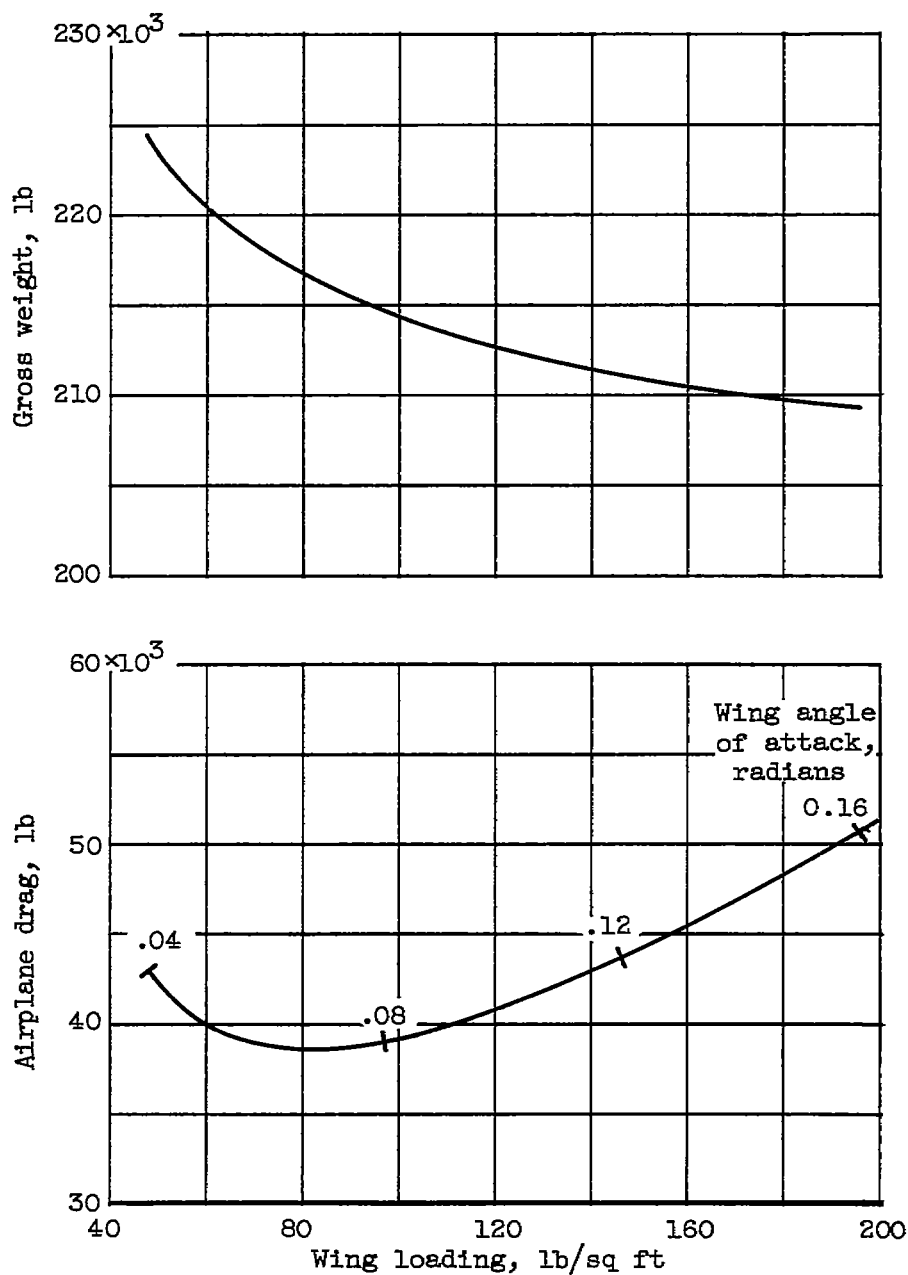


Figure 10. - Effect of variation in wing loading. Altitude, 70,000 feet; two engines; shield weight, 100,000 pounds.

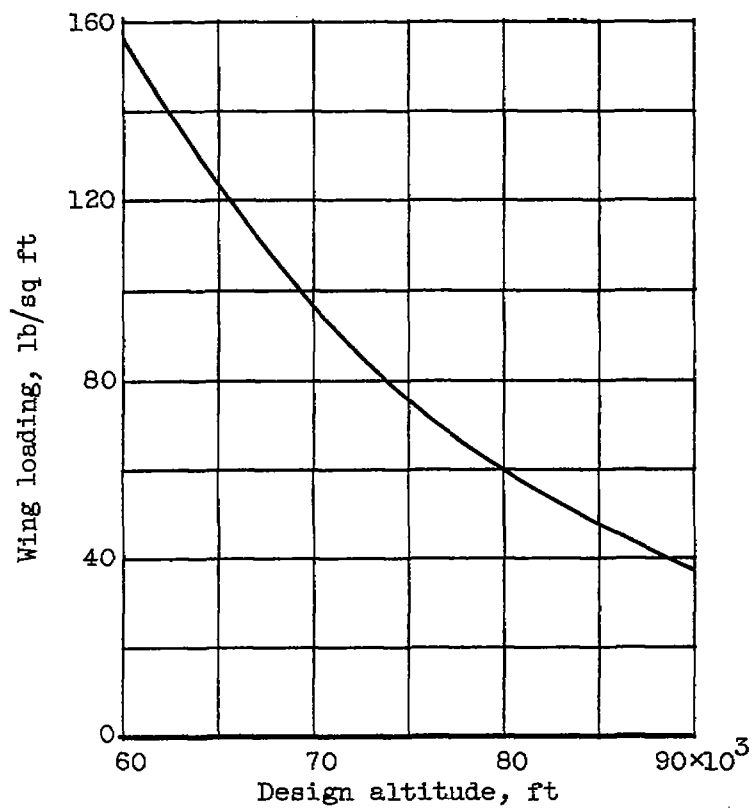


Figure 11. - Variation in assigned wing loading with design flight altitude.

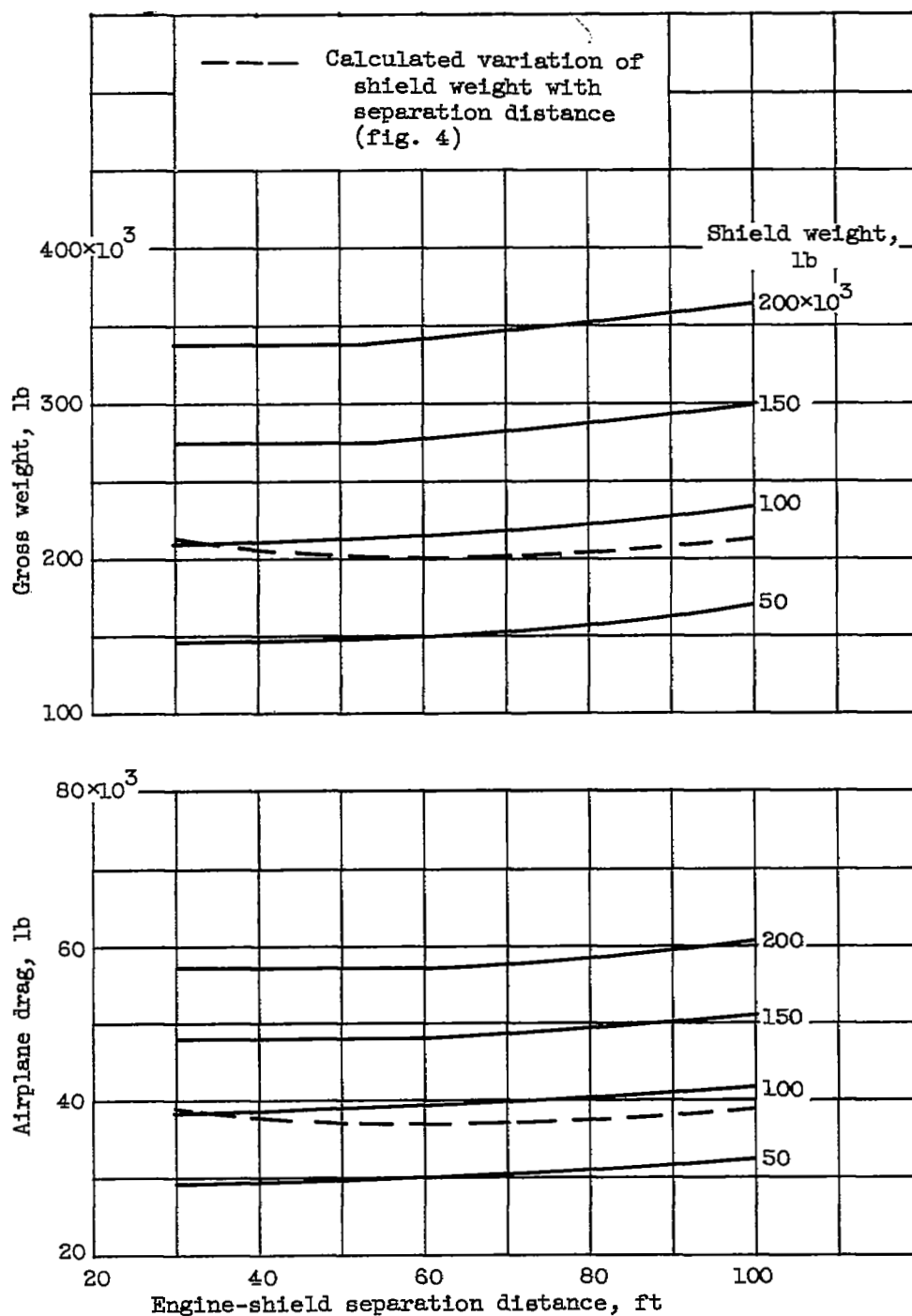


Figure 12. - Effect of variations in shield weight and separation distance between engines and shield. Altitude, 70,000 feet.

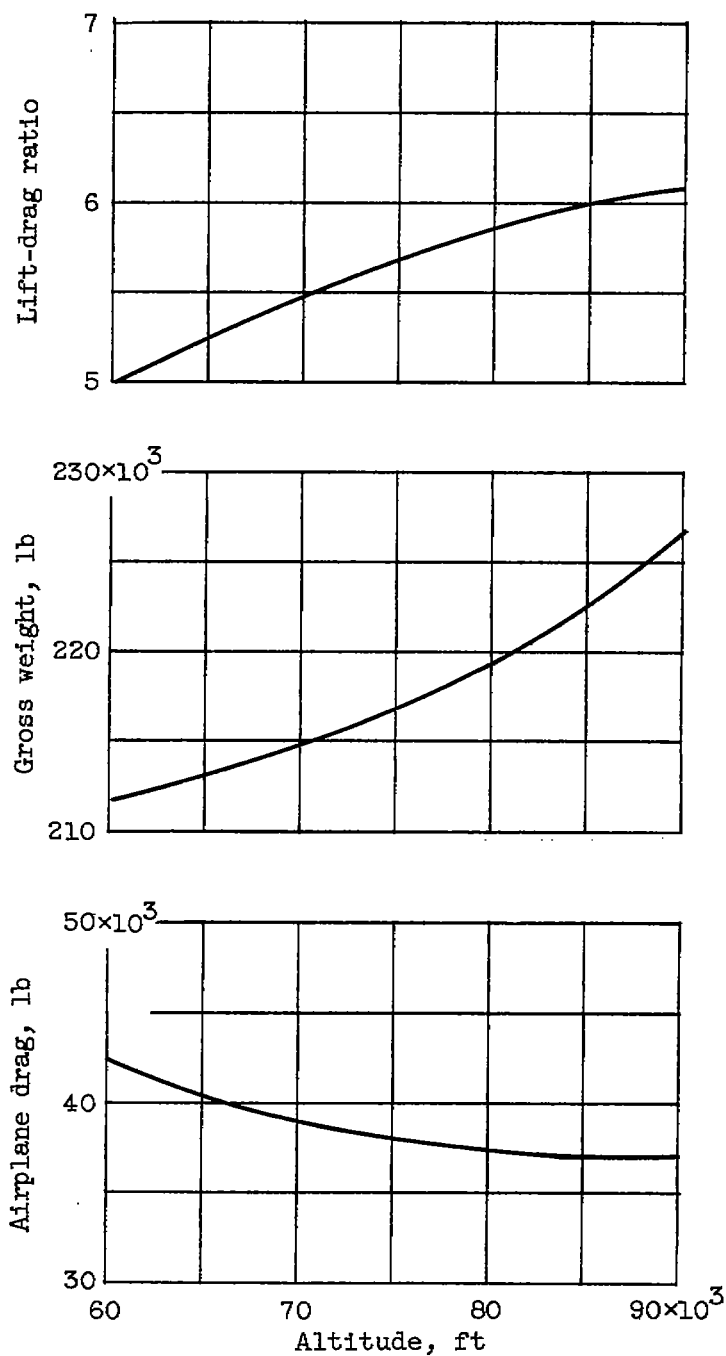


Figure 13. - Effect of variation in design flight altitude. Two engines; shield weight, 100,000 pounds.

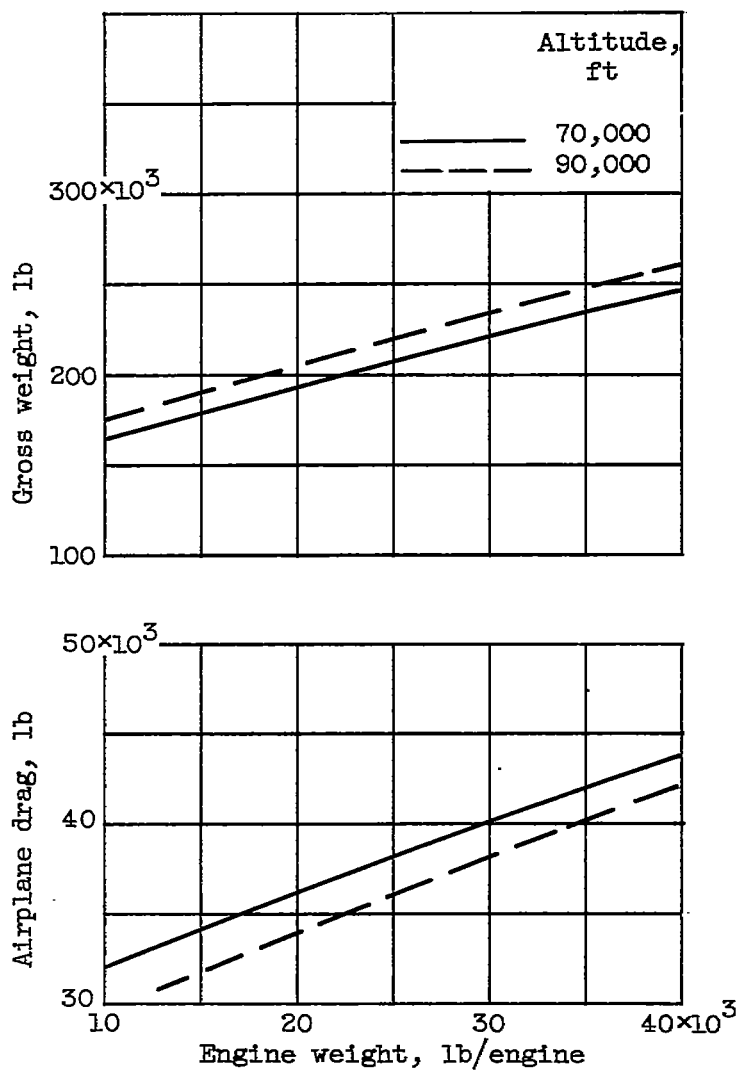


Figure 14. - Effect of variation in engine weight. Two engines; shield weight, 100,000 pounds.